

Optical vault: reconfigurable bottle beam by conically refracted light

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We employ conical refraction of light in a biaxial crystal to create an optical bottle for trapping and manipulation of particles. We show that by just varying the polarization of the input light the bottle can be opened and closed at will. We experimentally demonstrate stable photophoretic trapping and controllable loading and unloading of light absorbing particles in the trap.

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I. INTRODUCTION

Since its inception in the late 70s the field of optical trapping and manipulation of micron and submicron-sized objects with light has experienced an intense interest and rapid development [1, 2]. Optical tweezers utilising the presence of mechanical forces arising from light interaction with matter are now an indispensable tool in various physical, biological and medical applications. They have been extensively used in manipulating colloidal particles, molecules, nanoparticles and even single atoms. The recent decade has seen an enormous progress in the field of trapping resulting in the implementation of advanced techniques involving for instance, multiple holographic traps, optical fibers, or singular scalar and vector beams [3, 6, 9]. Optimum conditions for particle trapping are dictated by the optical properties of the particles and the surrounding medium, as well as the physical nature of the light-mediated trapping forces. For instance, while high light intensity attracts and traps transparent high-index objects in a low-index medium, it in fact repels low index particles in a high index environment [4]. That is why hollow (or donut) beams are used for efficient trapping in the latter case. In general, depending on the particular media and application, robust trapping and manipulation of micro-objects requires tailoring the light beam intensity pattern via phase and amplitude modulation or by varying spatial coherence of light [7–11].

In 2000, Arlt and Padgett [12] introduced the concept of an optical bottle which represents an optical beam with a low (ideally null) intensity region surrounded entirely by light. Such a bottle could be used as a three-dimensional trap. Following this idea various practical implementations of optical bottles have been proposed. The low intensity regions have been formed using, for instance, interference of multiple laser beams, partially spatially coherent optical vortices or laser beams affected by optical aberrations. The suitability of an optical bottle for particle trapping and manipulation has been confirmed in experiments with atoms [13–15] and absorbing particles [16]. The concept of an optical bottle has also

been recently extended to plasmonic structures [17].

The problem with an ideal bottle beam is that the more efficiently it traps particles the more difficult it is to actually load it with the particles. Once an optical bottle is formed it actually prevents particles from entering it [5]. To cope with this issue, one straightforward solution consists of turning on the bottle beam when the particles already float in the region where the trap will be formed. Another and much more convenient choice would be to design a bottle in such a way that it could be partially opened and closed so it could be loaded and unloaded with particles as required.

The purpose of this work is to prove that such a design is indeed possible. We will demonstrate that an optical bottle formed by using conically refracted light in a biaxial crystal could be controlled so it can be opened and closed at will and in real time by varying the polarization of the input beam. We will then use photophoretic trapping to demonstrate loading and unloading of airborne particles into and from the bottle.

II. THEORY

Conical refraction refers to the phenomenon associated with the propagation of a collimated optical beam along one of the optical axes of a biaxial crystal [18]. Conical refraction was first studied by Hamilton, who predicted that light emerging from the crystal should exhibit conical-like intensity distribution, which was observed soon afterwards by Lloyd [J. G. OHara, The prediction and discovery of conical refraction by William Rowan Hamilton and Humphrey Lloyd, Proc. R. Ir. Acad. 82 (2), 231257 (1982).]. The geometric optic approximation for the conical refraction ring radius is given by $R_0 = l\alpha$, being l the length of the biaxial crystal and α its conicity. A close observation of the ring pattern reveals that it is indeed formed by two concentric bright rings, the so-called fine Poggendorff splitting. In fact, for a focused input beam, the bright ring with the Poggendorff splitting appears at the focal plane of the lens which is a symmetry plane of the beam evolution. Out of this plane,

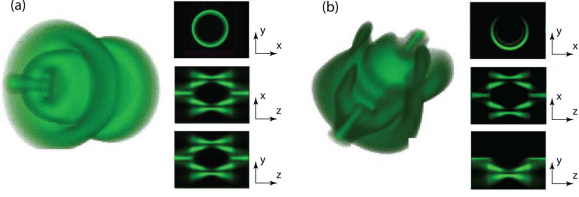


FIG. 1. (color online) Calculated light intensity distribution of conically refracted light beam in biaxial crystal. (a) circular polarization (Eq.(1)) leads to a fully closed optical bottle; (b) linearly polarized input beam (Eq.2) leads to an open-top optical bottle. The insets depict the principal cross sections of the light intensity distribution. Here $\rho_0 = 10$.

two bright on-axis spots are observed symmetrically at both sides which are named as Raman spots. It turns out that the actual light intensity distribution outside the crystal is strongly determined by the initial parameters of the beam such as its polarization, orientation, and the degree of focusing given by $\rho_0 = R_0/w_0$ where w_0 is the beam waist radius. Varying these parameters one observes either a single spot or a ring pattern.

It is worth noting that the ring intensity pattern combined with a nontrivial polarization structure of the conically refracted light has been already employed in trapping of micro-objects. However, in this case the beam was used to form traditional tweezers for two-dimensional manipulation of particles [19, 20]. Here we are interested in the three-dimensional 3D structure of the conically refracted light. In the paraxial regime the light intensity distribution at a distance z behind the biaxial crystal can be analytically described as [21]

$$I_{CP}(\rho, z) = |B_C|^2 + |B_S|^2 \quad (1)$$

for a circularly polarized beam, and

$$I_{LP}(\rho, z) = I_{CP} + (B_C B_S^* + B_C^* B_S) \cos(2\Phi - (\varphi + \varphi_C)) \quad (2)$$

for a linearly polarized input beam. Here $\vec{\rho} = (\cos \varphi, \sin \varphi)$ represents transverse coordinates, Φ is the angle of the initial linear polarization and φ_C defines the orientation of the plane of the crystal's axes. Functions $B_S(\rho, z)$ and $B_C(\rho, z)$ are defined as

$$B_C(\rho, z) = \int_0^\infty \eta a(\eta) e^{-i\frac{\pi}{4}\eta^2} \cos(\eta\rho) J_0(\eta\rho_0) d\eta \quad (3)$$

$$B_S(\rho, z) = \int_0^\infty \eta a(\eta) e^{-i\frac{\pi}{4}\eta^2} \sin(\eta\rho) J_1(\eta\rho_0) d\eta \quad (4)$$

$$a(\eta) = \int_0^\infty \rho E^{in}(\rho) J_0(\eta\rho) d\rho \quad (5)$$

where $E^{in}(\rho)$ is the amplitude of the input beam and $\eta = |\vec{k}_\perp|/w_0$. According to Eq.(1), for a circularly polarized input beam the light intensity distribution behind the crystal forms a cylindrically symmetric structure. One can show [22] that for $\rho_0 \gg 1$, the previous

equations describe the formation of the well resolved ring at the focal plane as well as the bottle beam between the two Raman spots. This situation is illustrated in Fig.1 (a) where we show the 3D light intensity distribution behind the crystal for $\rho_0 = 10$. One can clearly observe the existence of a dark region surrounded by high light intensity.

A more complex intensity pattern can be realized with a linearly polarized input beam. From the Eq.(2) one finds that the linear polarization results in the loss of perfect cylindrical symmetry. Instead of rings the transverse light intensity distribution has a form of crescents over certain finite distance. From the 3D perspective this indicates the formation of a hole in the side of the otherwise perfect bottle beam. This situation is depicted in Fig.1(b). The gap in the otherwise homogeneous intensity pattern is clearly visible. What is more important, the angular position of the gap can be varied by rotating the azimuth of the linear polarization of the input beam. The appearance of the hole in an optical bottle and the ability to vary its position provides a unique opportunity to control the trapping conditions. Opening the hole in the bottle would allow one to quickly load particles into the trap. The trap can then be closed by switching over to circular polarization. Reverting to the linear polarization would enable opening the hole in the trap at a desired angular location to unload the particles.

III. EXPERIMENT

We tested experimentally the practical suitability of the above described optical bottle beams for trapping of airborne microscopic particles. The experimental setup is schematically depicted in Fig.2. The light beam from a cw laser ($\lambda=532\text{nm}$, input power 100mW) passes through a $\lambda/2$ and $\lambda/4$ wave plates and then, after focusing with 100 cm positive lens, propagates along the optical axis of a monoclinic KTP crystal ($l = 10\text{mm}$ and $\alpha = 0.010\text{ mrad}$) cut perpendicular to one of its optic axes, giving $\rho_0 \approx 12$. Light emerging from the crystal is imaged with a CCD camera. We start with a circularly polarized input beam to create a perfect, cylindrically symmetric optical bottle. In order to visualize the optical bottle the camera was translated axially with a $10\mu\text{m}$ step and at each step the transverse light intensity distribution is recorded and stored in the computer. A sequence of 75 intensity slices is then used to reconstruct the full 3D structure of the bottle. The result is depicted in Fig.3(a) and accompanying movie. It is evident that the conically refracted light does form an optical bottle with a dark central region entirely surrounded by light. The transverse size and the length of the bottle could be adjusted by varying the collimating optics as well as the position of the crystal. In the next step the polarization of the input beam is changed to linear. The corresponding 3D light intensity distribution is shown in Fig.3(b) and accompanying movie. The structure is no longer

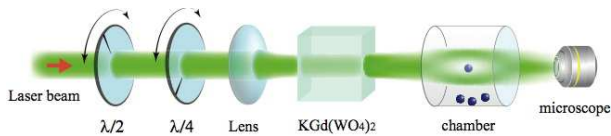


FIG. 2. (color online) Experimental setup.

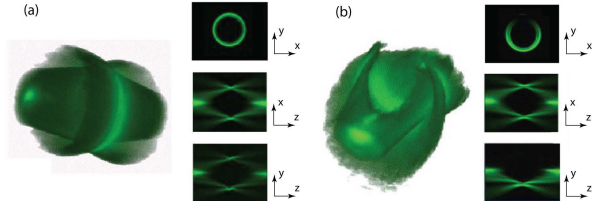


FIG. 3. (color online) Experimentally recorded 3D structure of an optical bottle beam formed by the conical refraction of light in a $\text{KGd}(\text{WO}_4)_2$ crystal. (a) The bottle is fully closed for a circularly polarized incident beam and (b) open for a linearly polarized incident beam. The hole in the top wall of the “bottle” is clearly visible. The insets depict the principal cross sections of the light intensity distribution. Here $\rho_0 \approx 12$

cylindrically symmetric, with the top wall of the bottle featuring an opening, in agreement with the theoretical prediction [see Fig.1(b)].

We used the optical bottle depicted in Fig.3 to demonstrate trapping and manipulation of airborne light absorbing particles. Such particles can be efficiently confined by employing the photophoretic force [16, 23]. In this case the illumination of particles leads to their heating and nonuniform temperature distribution. Interaction with the surrounding air results in appearance of the photophoretic force which tends to repel particles from the high intensity region. We have recently demonstrated efficient photophoretic trapping and transport of micrometer size particles over large distance of tens of centimeters [26, 29]. In our experiments with the optical bottle we used glass shells covered with a thin layer of carbon (200nm) in order to enhance the light absorption. The external diameter of the shells varied ranging from a few to tens of micrometers. To prevent accidental air flow from affecting the trapping the optical bottle was formed inside a transparent glass cell placed immediately behind the biaxial crystal. The axially located CCD camera recorded images of the particles inside the optical bottle. In order to speed up the trapping process the spheres were made floating in the air.

We found that while a particle could be trapped using either a fully closed (circular polarization) or open (linear polarization) bottle, the loading process was much quicker in the latter case. As the internal diameter of the bottle was rather large ($200\ \mu\text{m}$) the bottle could accommodate a great variety of trapped spheres. In Fig.4 we show three examples of particles with different size confined in the trap. Because of gravity they are all lo-

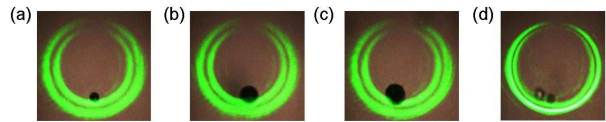


FIG. 4. (color online) Experimental images of hollow glass shells of different size trapped inside the bottle beam. In (a-c) shell diameter is $21\ \mu\text{m}$, $45\ \mu\text{m}$, and $50\ \mu\text{m}$, respectively. (d) Simultaneous trapping of two glass spheres. Here $\rho_0 \approx 12$.

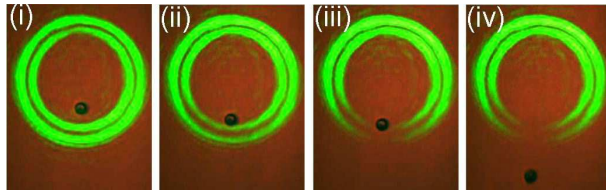


FIG. 5. (color online) Experimentally recorded sequence of images illustrating unloading the trapped glass sphere from the bottle. The sequence of graphs (i)-(iv) represents different stages of the opening the gap in the bottom side of the bottle. Here $\rho_0 \approx 12$.

cated at the bottom of the bottle. The trapping was generally very robust, with the particles stably resting on the lower “wall”. However, we found that sometimes the trapped particles oscillated inside the trap with the oscillation frequency increasing with the trapping power. Such a dynamics was observed in the case of trapping complex objects such as those formed by two connected glass spheres.

The ability to open or close the bottle at will by varying the polarization of input beam gives a unique opportunity to use the opening in the bottle not only to easily trap micro-object but also unload the trap. Such functionality is demonstrated in Fig.5. The image sequence represents various stages of closing the hole in the upper wall of the bottle while simultaneously opening it in its bottom wall. It is clearly seen that the initially stably trapped sphere drops out of the trap under gravity when the hole in the bottom wall opens.

IV. CONCLUSIONS

In summary, we have employed conical refraction of light in a biaxial crystal to create an optical bottle for trapping and manipulation of airborne particles. We have demonstrated that by just varying the polarization of the input light the bottle can be opened and closed. We have also experimentally demonstrated stable photophoretic trapping and controllable loading and unloading of particles in the trap.

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